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Evaluation of a Kinetic Modeling Approach to Aircraft Trajectory Prediction in the En Route Automation Modernization System

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16. Abstract

Accurate trajectory prediction for aircraft during arrivals is complex. The legacy En Route Automation Modernization (ERAM) Trajectory Modeler (TM) performs well when dealing with step descents, but is based on empirical data and at present does not properly support flights that engage in idle-thrust descent. The Kinetic Vertical Model (KVM) is a physics-based prototype enhancement to the ERAM TM that makes use of enhanced aircraft intent information, either provided directly or inferred, in order to allow for appropriate idle-thrust descent modeling. This enhancement is incorporated into a Hybrid-KVM model that produces legacy behavior when rich intent information is not available and produces prototype behavior when rich intent is available and idle-thrust descent is imminent. The Hybrid model shows greatly improved Top of Descent prediction and reduced trajectory error in both the vertical and along track dimensions during the descent phase.

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Executive Summary

The Separation Management and Modern Procedures Project is an initiative of the Federal Aviation Administration (FAA) under the Next Generation Air Transportation System (NextGen) Program to implement improvements in the En-Route Automation Modernization (ERAM) system, which supports all en-route facilities in the United States. The FAA's Air Traffic Organization En-Route Program Office (ATO-E) has tasked the FAA's Concept Analysis Branch (ANG-C41) to execute several studies investigating the impacts from various proposed prototypes and parameter changes in ERAM's Conflict Probe Tool (CPT) and/or Trajectory Modeler (TM). The overall objective is to improve the performance of ERAM's CPT subsystem in preparation for integration of the CPT alert notification into the flight data block on the radar controller's main display. This specific study is designed to evaluate a prototype enhancement to aircraft trajectory modeling in the TM, referred to as Kinetic Vertical Modeling (KVM).

The CPT supports controllers by predicting potential conflicts between flights up to 20 minutes in the future. Trajectories are a primary input to the CPT, and the more accurate the trajectory the better the quality of the alerts generated by the CPT. Currently, descent prediction is performed using kinematic (or parametric) modeling. This modeling uses population-average information from lookup tables in order to obtain cruise speed, descent rate, and other factors for each aircraft at a given altitude and temperature. This information is used to determine Top of Descent (TOD), among other things, and works well for aircraft following step descents. At present, more flights are beginning to make use of advanced technologies to perform Continuous Descent Approaches (CDAs) at either idle-thrust or with a constant descent rate. The current kinematic model is based largely on empirical data primarily involving flights making step descents, and is inadequate when modeling idle-thrust descents. The KVM prototype is a kinetic (physics-based) model that attempts to use inferred or provided information about each individual aircraft when building trajectories.

The purpose of this study is to evaluate whether the KVM performs better than the legacy (kinematic) model when producing trajectories for flights that follow idle-thrust or near idle-thrust descent profiles. In addition, while the KVM may prove more capable of modeling idle-thrust descents which are becoming more prevalent in the National Airspace System (NAS), it may be unsuitable for modeling step-descent flights. A Hybrid-KVM model has also been proposed. This model would perform legacy TM by default and KVM when there is available enhanced intent information, such as Time Based Flow Management (TBFM) Ground Interval Management-Spacing (GIM-S) messages that provide speed profiles for arriving flights, suggestive of an idle-thrust descent. This would also preserve current functionality while providing enhanced functionality as flights following idle-thrust descents increase in frequency.

Analysis of TOD, descent rate, and trajectory accuracy for flights following idle-thrust or near idle-thrust strongly suggest that the Hybrid-KVM performed substantially better than the legacy TM. Accuracy in TOD prediction improved by almost 70% (approximately 100 seconds) with respect to the Baseline predictions. Descent rate improved by almost 300 ft./minute in the Hybrid model. Vertical trajectory error was reduced by almost 4000 ft. at the TOD and 500 ft. at the Bottom of Descent (BOD) while along track error improved by about 0.3 NM at TOD and almost 2 NM at BOD. In conclusion, it is recommended to continue development and evaluation of the KVM with more scenarios from different facilities, but the results in this study indicate that KVM will provide substantial improvement to ERAM's performance when implemented as envisioned. Furthermore, as the number of flights that perform these efficient idle-thrust descents increases, Hybrid-KVM will allow ERAM to reap further benefits in prediction performance.

Table of Contents

1. Introduction

The Separation Management and Modern Procedures Project is an initiative of the Federal Aviation Administration (FAA) under the Next Generation Air Transportation System (NextGen) Program to implement improvements to the National Airspace System (NAS) in the United States. The FAA's Air Traffic Organization En Route Program Office (ATO-E) has employed the FAA's Concept Analysis Branch (ANG-C41) to execute several studies investigating the impacts from various proposed prototypes and parameter changes to the Trajectory Modeler (TM) and/or Conflict Probe Tool (CPT) of the En-Route Automation Modernization (ERAM) system. The overall objective is to improve the accuracy of trajectories built by the TM which will improve the performance of the CPT subsystem in ERAM in preparation for integration of the CP alert notification into the flight data block on the radar controller's main display. This specific study is designed to evaluate the impact on trajectory accuracy of a Kinetic Vertical Model (KVM) prototype for the TM that makes use of EUROCONTROL's Base of Aircraft Data (BADA) [EUROCONTROL, 2014]. BADA contains information regarding aircraft performance, and this information is necessary when computing trajectories using a kinetic model.

The TM in ERAM currently uses a kinematic algorithm and lookup tables (Aircraft Characteristic Tables), hereafter referred to as the legacy model, when calculating Top of Descent (TOD) and descent rate/path. These predictions use lookup values dependent on aircraft type, altitude, and temperature. The KVM prototype created by the ERAM Development Contractor aims to provide an improvement to TOD prediction and descent rate for aircraft that descend at idle or near-idle thrust. For these aircraft, the prototype makes use of aircraft mass and speed profiles (or other enhanced intent information) which are either known or can be inferred. Specifically, flights following Optimized Profile Descents (OPD) and/or Continuous Descent Arrivals (CDA) will benefit from the KVM model. However, since these flights are not ubiquitous in the NAS, the prototype has been developed as a hybrid that allows for legacy descent predictions when flights do not follow idle or near-idle descents or when required intent information cannot be inferred. The hybrid model can make use of the more accurate kinetic modeling when flights are determined to be CDA and when the required information is available.

2. Methodology

This study is designed to evaluate the effect of utilizing BADA based Kinetic Vertical Modeling on aircraft trajectory accuracy in the ERAM system. The goal is to determine whether the Hybrid KVM model is able to operate under real world conditions in which intent about the aircraft is of varying quality and still improves trajectory accuracy with respect to legacy (baseline) ERAM performance.

2.1. *Data Flow*

This study used ERAM track, clearance, and wind data collected from Lockheed Martin's Sarbot tool. The data was recorded from the Seattle ARTCC (ZSE) on March 14, 2014. A subset of flights was identified as having profiles consistent with continuous or near-continuous descent arrival (CDA). For only these flights in the CDA set, the cruise altitude and Top of Descent (TOD) were determined, and an Interim Altitude (LH) message was created for each flight with altitude equal to the established cruise altitude. These experimental LH messages were then inserted into the original set of CMS messages with a message timestamp set to within a few seconds of 25 minutes prior to the established TOD for that flight, or at the time of earliest available track position should 25 minutes of track prior to the TOD be unavailable. The purpose for these LH messages is twofold. First, the insertion of these messages forces trajectories to be built approximately 25 minutes prior to the TOD for each CDA flight. This is critical as trajectory accuracy can vary significantly when look-ahead time varies; fixing the look-ahead time at 25 minutes greatly reduces potential variation in the results by forcing all trajectories used for analysis to be built at approximately the same time prior to TOD. Without the LH messages, the range of trajectory build times with respect to TOD could vary greatly and could not possibly be controlled. Second, 25 minutes prior to TOD corresponds to about 190 NM, the approximate position when messages from Time-Based Flow Management (TBFM) systems may be provided to a flight for the purposes of metering [Torres and Dehn, 2014]. Since part of the purpose of this experiment is to demonstrate the benefit of KVM when rich intent information is available, and since GIM-S (or pseudo GIM-S) messages associated with TBFM are a realistic implementation of rich intent information, it was logical to attempt to mimic operational use of TBFM when measuring the effect of KVM on trajectory accuracy.

The resulting track, clearance, and wind data were merged and run through Lockheed's VTL (lab ERAM) software, producing a 9 hour scenario. The scenario was used as an input to the FAA Concept Analysis Branch's analysis suite, *CpatTools*. These are comprised of a set of customized software that converts and filters input traffic files into a linked set of relational database tables including smoothed track data, calculated trajectory metrics, clearances, and routes for each flight in the scenario. All resulting analyses were performed using this data. No conflict prediction alert data was considered for this study.

2.2. *Analysis Methods*

The goal of this analysis was to evaluate trajectory accuracy after introduction of KVM to the Trajectory Modeler. KVM was applied to the scenario in several different ways, and was evaluated through analyses of the following scenarios:

- **Baseline** – Trajectories were produced using kinematic, or legacy, modeling for all flights.
- **KVM-All** (no GIM-S) – Trajectories were produced using KVM (kinetic) modeling for all flights.
- **KVM-Hybrid** – Trajectories were produced using KVM only for flights in the CDA set, and the insertion of pseudo GIM-S messages [Torres and Dehn, 2014] at 25 minutes from TOD further refined the KVM-based trajectories. Trajectories for all non-CDA flights were produced using kinematic legacy model only.

2.2.1. Data Collection and Reduction

Scenario information necessary for analysis was collected from the set of relational database tables described in Section 2.1. All data was collected via custom SQL queries and was imported into *JMP Statistical Discovery*[1] Software. There were 61 flights designated by Lockheed [Torres and Dehn, 2014] as CDA and consistent with idle or near-idle thrust, and this information was provided to the Concept Analysis Branch (CAB). For these flights, SQL *Oracle* queries were developed in order to gather various pieces of information. The trajectory that was built due to the

[1]JMP® is a commercially available software tool by SAS that provides the user with the capability to perform simple and complex statistical analyses. See http://www.jmp.com.

experimental LH messages described in Section 2.1 was identified and captured. The time and altitude at Top of Descent (TOD) was then calculated for track and trajectory in each scenario. In order to ensure that the segment of descent for each flight was relatively continuous, an analogous Bottom of Descent (BOD) was designated as the time each CDA flight first descended below 15,000 ft. This value was determined to be adequate through visual exploration of the descent segments for the identified CDA flights. Below 15,000 ft., restrictions, STARs, and other factors occasionally cause the TM to produce level segments, breaking the assumption of continuous descent, so 15,000 ft. was used to ensure homogeneity of the data.

Of the 61 flights identified as CDA, two were removed from analysis because the experimental LH messages were not processed properly in the VTL simulation, and associated trajectories were not built. Two additional flights were identified as not following descents consistent with idle thrust and were removed from the analysis. A final two (for a total of 6 flights removed) were not considered for analysis as *CpatTools* requires at least 40 seconds of track data prior to initiation of trajectory sampling, and the trajectories for these two flights were built prior to the requisite time having elapsed.

2.2.2. Metrics

Metrics for this study include a subset of the standard trajectory metrics used in many studies [Paglione and Oaks, 2007]. *Vertical Error* is defined as the vertical distance between a track point and its time coincident trajectory point, and *Along Track Error* is defined as the longitudinal distance between a track point and its time coincident trajectory point. *Cross Track Error*, the lateral distance between a track point and its time coincident trajectory point, was briefly examined; no effect was expected or observed.

In addition, metrics specific to examining TOD were introduced. *TOD Error* is defined as the difference in time between the track-determined TOD and the trajectory TOD, where negative values indicate that the predicted TOD occurred prior to the actual TOD. *Descent rate* is the actual (track) or predicted (trajectory) rate of descent of the aircraft over the region of time spanning the TOD to BOD.

3 Analysis

This section presents the results for trajectory metrics and descent data associated with Section 2.2. In addition, detailed flight examples that illustrate how the KVM algorithm affects trajectory modeling are also presented.

3.1 Descent Statistics

This section presents data indicating how the predicted descent metrics (Top of Descent, descent rate) compares to the flight track, or true descent. When comparing TOD, a perfectly accurate prediction would have an error of 0 seconds. Negative values indicate that the TOD was predicted earlier than truth whereas positive values indicate that the TOD was predicted after truth. Summary statistics are presented in Table 1. In the Baseline scenario, TODs tend to be predicted earlier than truth by about 2.5 minutes (149 seconds) which is a significant systematic difference. Application of the KVM algorithms to the TM (TOD-ALL) reduces the magnitude of this systematic error by more than half (52.2%), dropping from 149 seconds to 71 seconds. The reduction in magnitude, independent of sign, suggests that the KVM algorithms consistently predict a later descent than does the Baseline modeler. Additionally, the fact that the overall sign of the error for TOD-ALL becomes positive reveals that instead of just reducing the error, the KVM algorithm actually overestimated the TOD, which may reflect either the fact that the flights under consideration are not actually following true idle descent profiles, or may reflect that the KVM could be refined.

Table 1. Statistics for Top of Descent

	TOD-Baseline	TOD-ALL	TOD-Hybrid	Significance
Mean (seconds)	-149.0	71.2	47.9	p<.0001
SD (seconds)	101.5	82.6	73.2	p<.0001
N (CDA flights)	55	55	55	p<.0001

It should be noted that the KVM used assumptions of default BADA provided speed in the KVM-All scenario. In the TOD-Hybrid scenario, as mentioned previously, appropriate speed schedules were determined by post-analysis of the track data and were inserted into the VTL simulation along with the experimental LH messages as GIM-S style messages. This represents an ‘intent rich’ scenario consistent with a TBFM concept of operation. The improved intent reduces the magnitude error in TOD prediction even further (67.9%), from 149 seconds to 47.9 seconds. The sign of the error is again positive indicating overestimation of the TOD, but the additional intent information reduces the overestimation to 67% of the 71 seconds in the KVM-All scenario. Overall, TOD prediction was reduced on average from 2.5 minutes to .75 minutes, or 67.9 %, which is a sizable improvement with respect to Baseline.

The second aspect of descent, the descent rate from TOD to BOD, is presented in Table 2. Again, descent rate is presented with respect to the truth, so predictions that are perfectly accurate would have an error of 0. Negative values indicate that the predicted descent rate is faster (steeper) than the truth and positive values indicate that the predicted descent rate is slower (shallower) than the truth. In the Baseline scenario, the descent rate is underestimated (is too shallow) compared to the truth by an average of 373 ft./min. This is at least in part due to the fact that even when a TOD is predicted earlier, the metering fix for said flight is unchanged in space. This allows more time to descend to the altitude required by the metering fix (or by any type of altitude restriction), and results in a shallower descent. In contrast, later descents should be steeper, and this is what is seen in the KVM-All scenario; descent rates are 427 ft./min steeper than truth on average, which is a larger error than that seen in the Baseline scenario. The KVM-Hybrid scenario, on the other hand, has a descent rate error with the same sign as the KVM-All scenario, indicating a descent rate that is steeper than truth, but the magnitude is 93 ft./min less than that of the baseline corresponding to a 24.9% reduction in error - another sizable improvement with respect to Baseline.

Table 2. Difference between trajectory and observed path descent rates.

	TOD-Baseline	TOD-ALL	TOD-Hybrid	Significance
Mean (ft./min)	372.8	-426.5	-279.9	p<.0001
SD (ft./min)	279.4	299.4	282.8	p<.0001
N (CDA flights)	55	55	55	p<.0001

3.2 Trajectory Accuracy

Trajectory accuracy is a means of examining how well the parameters discussed above, TOD and descent rate, predict the track of each flight. TOD and descent rate essentially correspond to the intercept and slope of a linear model that fits the track during descent, so a trajectory analysis here becomes an informal goodness-of-fit test for the KVM Trajectory Modeler.

For analysis of flights in the CDA set, all trajectory errors are measured using the trajectory that was built 25 minutes prior to the TOD or the trajectory built at the earliest point prior to the TOD if 25 minutes of track are not available. Given this, standard Look Ahead Time values were not useful for the purposes of grouping data for analysis. So, TimeToTOD was calculated in order to normalize predictions based on when the true TOD actually occurred for each flight. For example, a TimeToTOD of -120 sec indicates that the TOD time will occur 2 minutes from that point in time, should the prediction be accurate.

First, trajectory accuracy around the TOD and the BOD is considered, where BOD is truncated to 15,000 ft., as previously discussed. Vertical error and along track error are shown around the TOD and BOD in Figure 1. At the point identified for each flight at the TOD, Vertical error (top left) is significantly higher in the Baseline scenario (4300 ft.) than in the KVM-All and KVM-Hybrid scenarios (760 ft. and 790 ft., respectively). Even though the TOD prediction in the KVM-All and KVM-Hybrid scenarios still deviates from the truth, as discussed in Section 3.1, the increased accuracy results in a reduction in vertical error around TOD of approximately 3600 ft., or more than 80%, primarily due to the fact that the predicted descent begins much closer to the true TOD in these two scenarios. This average improvement is maintained even by the time each flight reaches BOD (top right), though the improvement drops to 400 ft. (16%), which is expected as the BOD of a trajectory should be relatively close to a metering fix regardless of where the trajectory began.

Along track error around the TOD (bottom left of Figure 1) is 2.86 NM on average in the Baseline scenario. Enhanced TOD prediction improves this slightly as the KVM algorithm and pseudo GIM-S information are applied, reducing the error to 2.6 NM, a .26 NM or 9% reduction in error. At the BOD (bottom right of Figure 1), however, the accumulated effect of the improved TOD prediction and descent rate is evident. Along track error drops from 5.1 NM in the Baseline scenario to 3.19 NM in the KVM-Hybrid scenario. This is a reduction in error of 1.9 NM or 37.5%, which is again very significant.

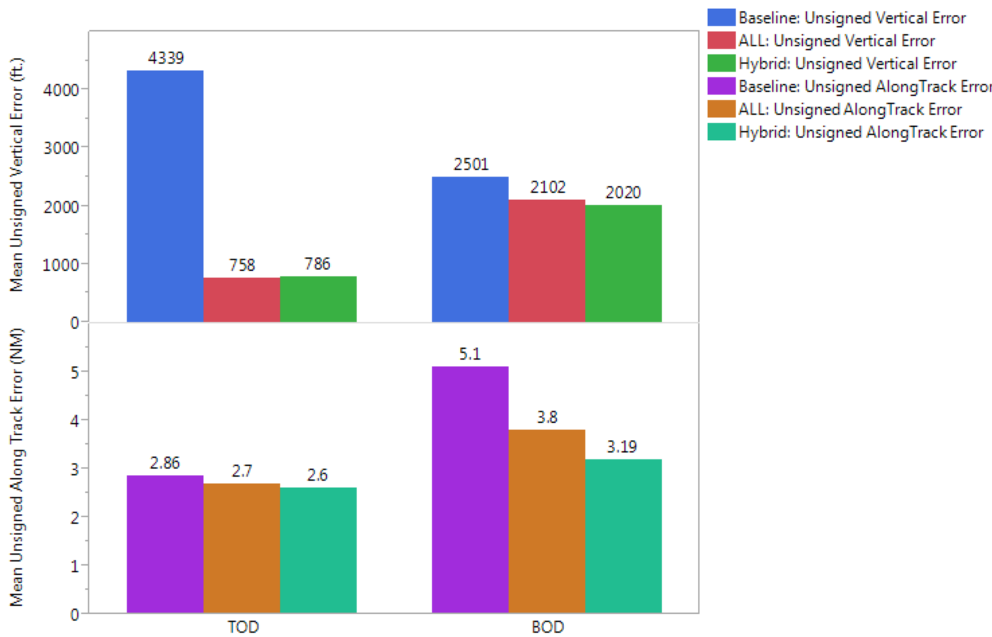

Figure 1. Vertical and Along Track Error at TOD and BOD.

In addition to examining trajectory accuracy around the TOD and BOD specifically, trajectory accuracy can be analyzed along the entire descent in order to verify that any improvements are not isolated to those critical points. Unsigned vertical error over the course of the descent is depicted in Figure 2. The time relative to the TOD (TimeToTOD) is indicated on the abscissa. Magnitude of the vertical error in the Baseline scenario (top, blue bars) begins to increase at about 400 seconds prior to the TOD, and reaches a peak at the time of the true-TOD, which is consistent with an early predicted TOD. As the TimeToTOD approaches 0 sec, the vertical error in the KVM-All and KVM-Hybrid scenarios begins to increase, becoming largest after the true-TOD, which is consistent with a late predicted TOD. The bottom of the figure depicts the difference in error magnitude when comparing Baseline and KVM-All/KVM-Hybrid scenarios over time. Prior to the TOD, the KVM-All/KVM-Hybrid scenarios show a significant reduction in vertical error (negative values) which reaches an improvement of about 3700 ft. at the peak. Following the TOD and during the descent this trend reverses slightly, with the Baseline vertical error about 500 ft. better than the KVM-All/KVM-Hybrid error at the peak. Overall, however, the improvement in vertical error significantly outweighs any degradation.

Unsigned along track error is depicted in Figure 3. The time relative to TOD (TimeToTOD) is again on the abscissa. Magnitude of the vertical error (top, blue bars) gradually increases from about 2 NM at 6 minutes prior to the true TOD time up to 5.1 NM at the calculated BOD (15,000 ft.). The along track error for the two treatment scenarios (KVM-All, KVM-Hybrid) begins at 2 NM as well. There are two primary potential causes for the 2 NM error observed at the 19 minute look ahead in all 3 models; how the cruise speed is modeled and error in wind accuracy [Schwartz et al., 2000]. The key element, however, is that the rate of increase over time is greatly reduced so that at BOD the along track error has only reached an average of 3.8 NM in the KVM-All scenario (a reduction of 1.2 NM), and 3.2 NM in the KVM-Hybrid scenario (a reduction of 1.9 NM). The improvement over time is due solely to the KVM as all other factors are identical. This is indicated in the bottom half of Figure 1, where the purple bars represent the KVM-All scenario and the orange bars represent the KVM-Hybrid scenario. The reduction in along track error in the both the KVM-All (25%) and the KVM-Hybrid scenario (37%) is sizable.

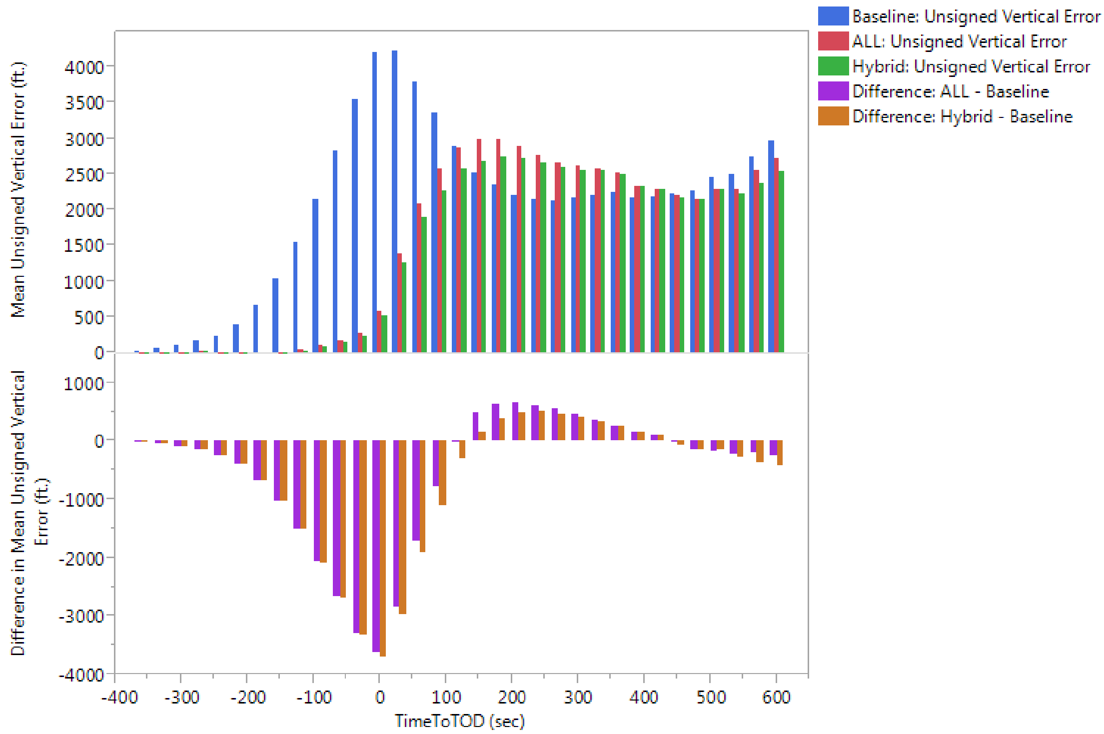

Figure 2. Vertical trajectory error over the descent.

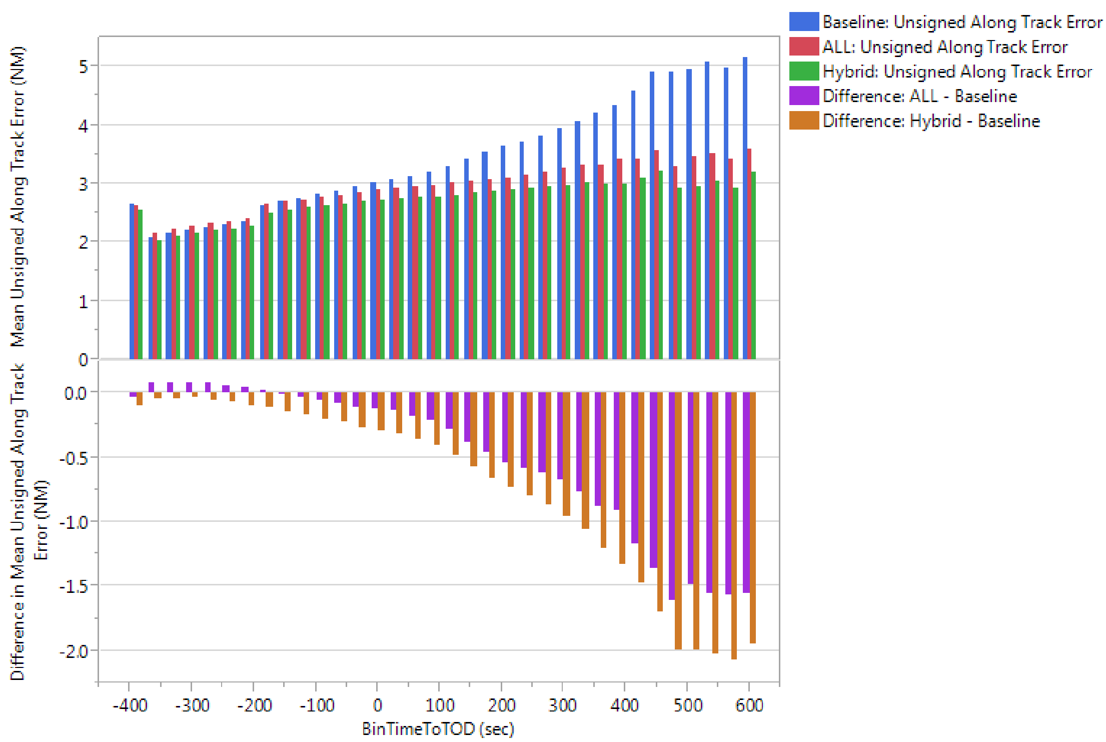

Figure 3. Along track trajectory error over the descent.

Evaluation of trajectory accuracy for the non-CDA flights in the KVM-ALL scenario was performed in order to see how much, if any, degradation occurs when the KVM is applied to flights that don't meet the basic assumptions necessary for KVM; namely, idle or near-idle descent. All trajectories built between 25 minutes prior to TOD and when the flight descended to 15,000 ft. (both based on track) were considered in this analysis and sampled using the Interval Based Sampling Technique (IBST) described in Paglione and Oaks [2007]. The trajectory accuracy should be typical of what one would expect were the KVM prototype applied to ERAM wholesale, replacing the legacy trajectory modeling and disregarding the scalability of the Hybrid model. Average unsigned trajectory errors for non-CDA flights in the Baseline and KVM-All scenarios are shown in Table 3, filtered to exclude data for a given trajectory that is beyond any clearances which reflect a change in intent after the trajectory build time, which is standard practice when applying the IBST. The changes in average unsigned error for non-CDA flights due to the KVM prototype can be seen in Table 4, in which the difference between the metrics in the Baseline and KVM-All scenarios are also depicted. When examining the difference between the two scenarios, negative values indicate improvement in the metric when the KVM prototype is applied and positive values indicate degradation. It is evident when examining Table 3 and Table 4 that the difference in vertical error between the two scenarios is negligible. It is well below 300 ft. at all look ahead times, and the difference between the two scenarios is only significant at a look ahead time of 0 seconds. In contrast, the difference in along track error is negligible at look ahead times of 0 and 300 seconds, but becomes significant and increases in magnitude from -.23 NM to -.61 NM as the look ahead time increases from 600 seconds to 1200 seconds. Together, these two metrics suggest that on average the KVM prototype does provide slight trajectory accuracy gains in the along track dimension while not degrading the vertical dimension. It should be noted that the gain in along track accuracy is likely due to the fact that along track (longitudinal errors) depend on the modeled descent speed, which implies that the BADA default speeds used in the KVM-All scenario are better than the speeds used in the legacy lookup tables.

Table 3. Average unsigned trajectory errors (non-CDA flights) for Baseline and KVM-All scenarios.

	Baseline Vertical Err. (ft.)	Baseline Along Track Err. (NM)	All Vertical Err. (ft.)	All Along Track Err. (NM)	N
Look Ahead 0	406.9 [738]	1.09 [3.0]	364.2 [559]	1.05 [2.9]	1135
Look Ahead 300	992.5 [1379]	2.64 [4.4]	970.3 [1185]	2.67 [4.27]	1104
Look Ahead 600	938.4 [1519]	3.75 [6.0]	964.7 [1511]	3.98 [5.8]	1046
Look Ahead 900	737.5 [1604]	4.73 [7.8]	732.5 [1551]	5.24 [8.1]	920
Look Ahead 1200	537.0 [1737]	5.58 [10.0]	509.7 [1604]	6.19 [10.2]	794

Table 4. Difference in trajectory metrics (non-CDA flights) between Baseline and KVM-All scenarios.

	All - Baseline Vertical Err. (ft.)	All - Baseline Along Track Err. (NM)	N	p-Vertical	p-Along Track
Look Ahead 0	42.7 [346]	.04 [.9]	1135	p<.0001	p=.09
Look Ahead 300	22.2 [5279]	-.03 [.7]	1104	p=.16	p=.20
Look Ahead 600	-26.3 [544]	-.23 [1.5]	1046	p=.12	p<.0001
Look Ahead 900	5.0 [561]	-.50 [2.2]	920	p=.79	p<.0001
Look Ahead 1200	27.3 [504]	-.61 [2.7]	794	p=.13	p<.0001

3.3 Flight Examples

In the following examples, the track of each flight is represented by dotted lines. Blue wireframes represent the Baseline trajectories, red wireframes represent trajectories from the KVM-All scenario, and green wireframes represent trajectories from the KVM-Hybrid scenario. Cylinders of the same colors depict where the flight was predicted along the trajectories at the true TOD time. Examples 1 and 2 provide close-up examples of how well the KVM-Hybrid (with GIM-S) matches the TOD and descent rate of the true descent. Example 3 provides an example of what can happen when intent information does not match the true aircraft descent, in this case due to a modeling issue in ERAM.

3.3.1 Flight Example 1

Example 1 depicts a Boeing 737-800 (B738) out of San Jose International Airport (KSJC) cruising at FL 400 about 25 minutes before its true TOD at 54900 sec (Figure 4). The flight is preparing for descent into Portland International Airport (KPDX). A close-up view of the trajectories near the TOD are shown in Figure 5 Note that the blue (Baseline) trajectory begins descent 330 seconds (5.5 minutes) before the true TOD (dotted line). The trajectory from the KVM-All scenario (red) predicts descent to begin at 54957 sec. This is 57 seconds after the true TOD, but still about 4.5 minutes closer to the true TOD than the Baseline prediction. The predicted TOD in the KVM-Hybrid scenario (green) is at 54908 sec, only 8 seconds after the true TOD and over 5 minutes closer to the true TOD than the Baseline.

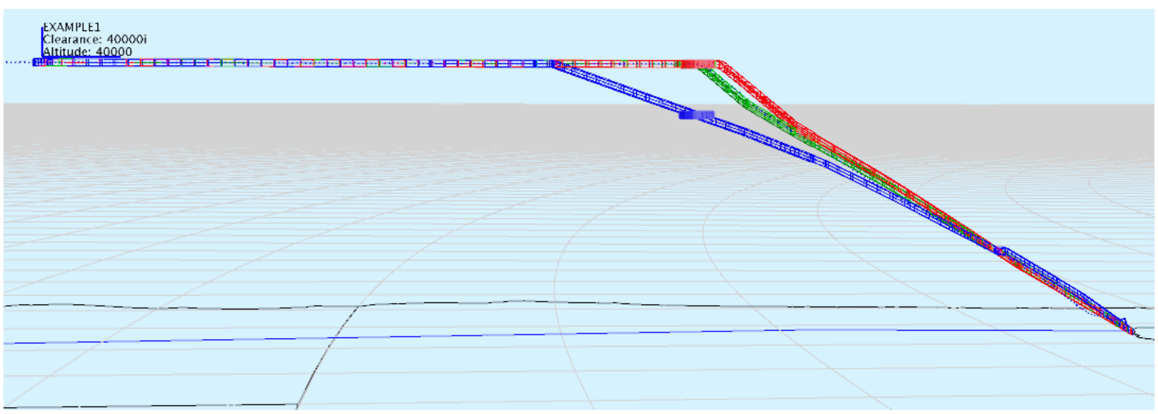

Figure 4. Example 1, side view.

Effects on the descent rate, also visible in Figure 5, are harder to extract from the image at first glance. However, it is obvious that the average descent rate in the Baseline scenario (1600 ft/minute) is shallower than the true descent rate (2300 ft/min), which closely follows the KVM-Hybrid prediction. The lookup tables used in the legacy modeling are primarily based on empirical data which does not contain significant numbers of CDA flights at present. Since the empirical data is biased towards step descents which are significantly shallower than idle thurst descents, underestimation of descent rate for CDA flights in the legacy model is expected. The descent rate for the KVM-All trajectory (red) is 2600 ft/min, which is about 300 ft/min steeper than the truth, and the descent rate for the KVM-Hybrid trajectory (green) is almost identical to that of the track.

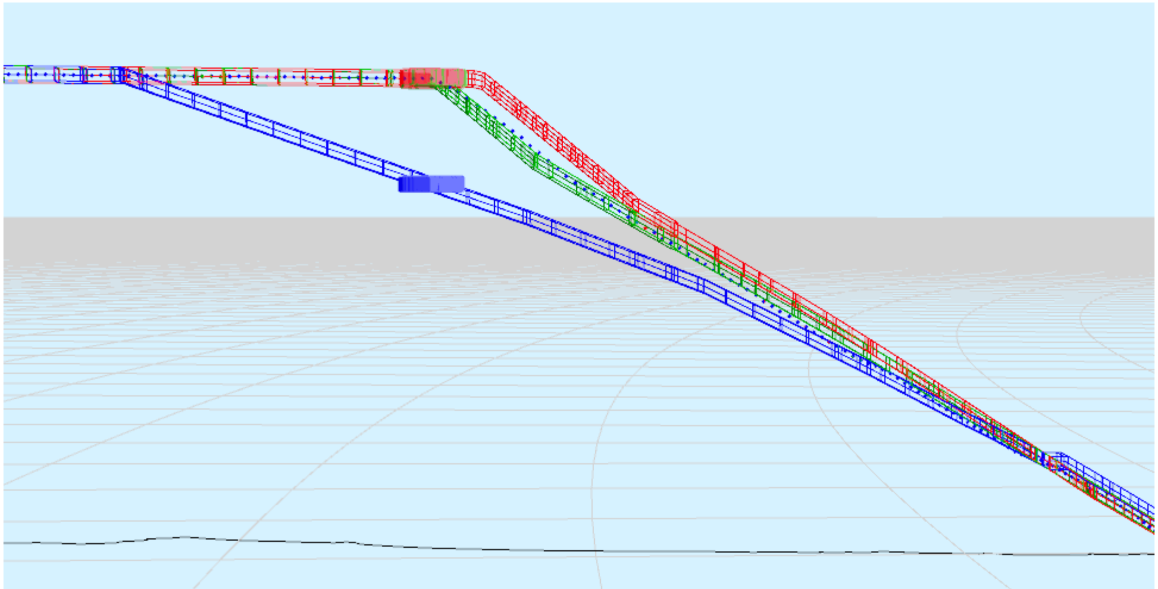

Figure 5. Example 1, close-up view of descent.

3.3.2 Flight Example 2

Example 2 evaluates a Boeing 737-700 (B737) out of San Jose International Airport (KSJC) cruising at FL 400 about 25 minutes before its true TOD at 74540 sec, depicted in Figure 6. The flight is preparing for descent into Portland International Airport (KPDX). A close-up view of the trajectories near the TOD is shown in Figure 7. Note that the blue (Baseline) trajectory begins descent 138 seconds (about 2 minutes) before the true TOD (dotted line). The trajectory from the KVM-All scenario (red) predicts descent to begin 111 seconds after TOD at 74651 sec., which is 27 seconds closer to the true TOD than the Baseline. The predicted TOD in the KVM-Hybrid scenario (green) is at 74557 sec, only 17 seconds after the true TOD and over 2 minutes closer to the true TOD than the Baseline. Again, the TOD is predicted too early when using the Baseline TM and too late when using the KVM, though the KVM tends to be better than the Baseline and improves even further when non-default speed schedules are used in the KVM-Hybrid model.

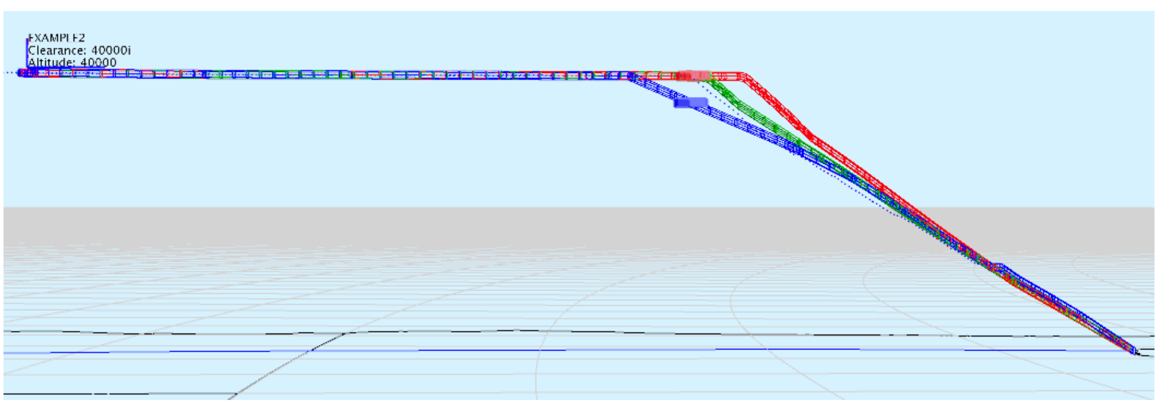

Figure 6. Example 2, side view.

Descent rate, visualized in Figure 7, is about 2200 ft./min from TOD to BOD (15,000 ft.). In this example, the Baseline rate is about 1950 ft./min, or 250 ft./min too shallow. The trajectory from the KVM-All scenario (red) predicts the descent rate to be about 2800 ft./min, about 600 ft. too steep compared to the true path. The KVM-Hybrid model predicts the descent rate to be about 2175 ft./min, which is only 25 ft./min different from the observed value.

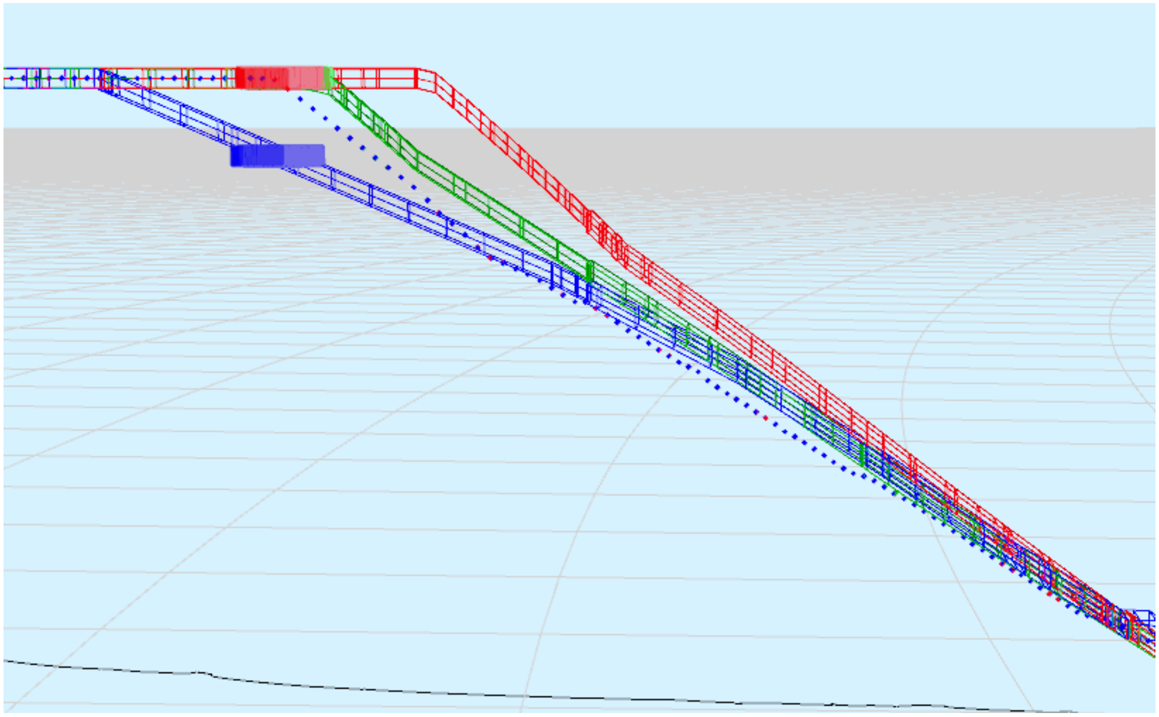

Figure 7. Example 2, close-up view of descent.

3.3.3 Flight Example 3

Example 3 evaluates an Airbus A320 (A320) out of San Francisco International Airport (KSFO) cruising at FL 450 about 25 minutes before its true TOD at 51630 sec, depicted in Figure 8. The flight is preparing for descent into Portland International Airport (KPDX). A close-up view of the track and trajectories near the TOD are shown in Figure 9.Figure 5 Note that in this example the blue (Baseline) trajectory significantly outperforms the TOD prediction in the treatment trajectories. The Baseline trajectory predicts that the TOD begins only 27 seconds after the true TOD, while the KVM-All and KVM-Hybrid trajectories predict the TOD 184 sec and 179 sec after the true TOD. The cause for this error is a modeling issue in the laboratory version of ERAM (VTL), identified by Sergio Torres of Lockheed Martin [personal communication, 12/17/2014]. Specifically, it was discovered that an ERAM algorithm, unrelated to the KVM prototype, did not allow the cruise speed provided in the pseudo GIM-S message to be used under certain conditions. This issue has been corrected in the ERAM VTL system [S. Torres, personal communication, 1/27/2015], but due to time constraints could not be applied to the scenarios for this experiment.

Descent rates are also influenced by this issue, as TOD greatly affects the descent rate required to meet a metering fix; a later TOD requires steeper descent so that a fix can be met in time. The true descent rate is about 2050 ft./min and Baseline rate is also about 2050 ft./min. In contrast, the KVM-All and KVM-Hybrid descent rates are 2750 ft./min and 2700 ft./min, respectively. These rates are about 700 ft./min too steep, consistent with an overestimation of TOD.

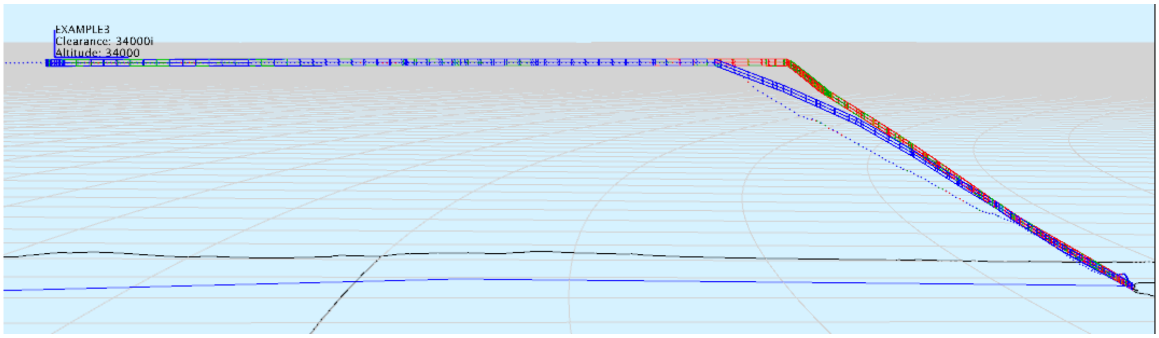

Figure 8. Example 3, side view.

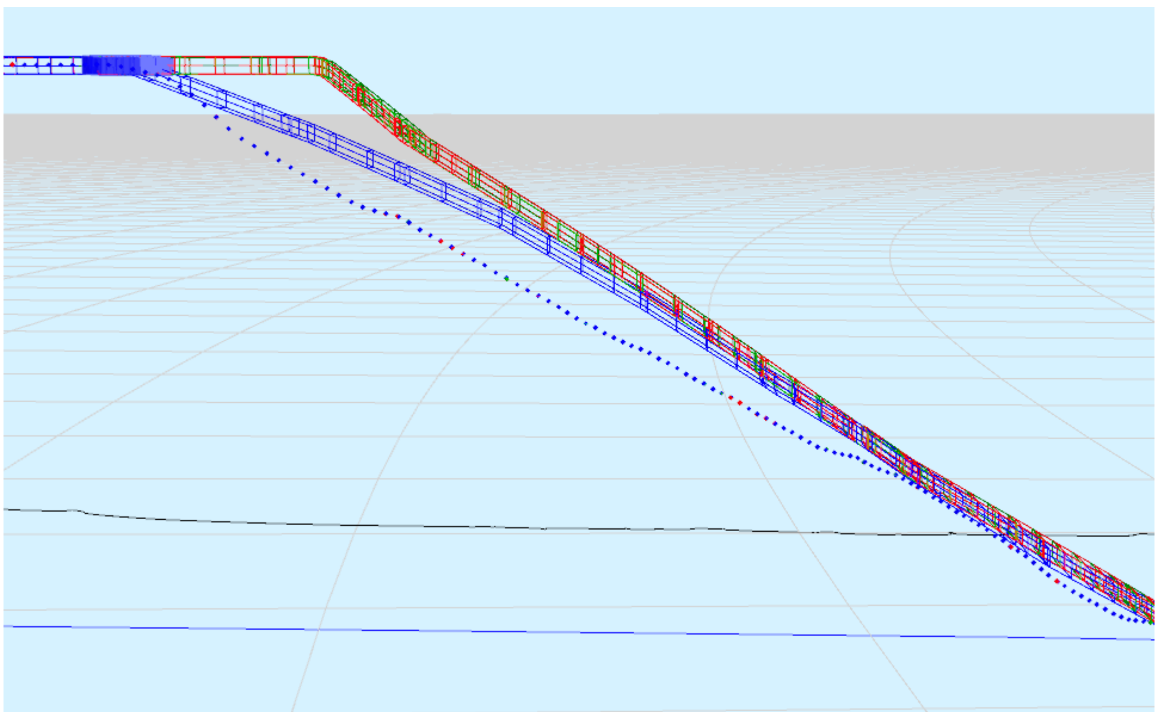

Figure 9. Example 3, close up view of descent.

4 Conclusions and Discussion

Trajectories are created by the ERAM system as a means of supporting the controller by predicting conflicts that may occur up to 20 minutes in the future. The accuracy of these predicted conflicts are affected by many factors. Fundamentally, however, the conflict probe's accuracy is directly dependent on the accuracy of the underlying 4-D trajectories used to make the conflict predictions. It has been shown previously that inaccurate trajectories can lead to degradation of performance in the ERAM Conflict Probe and an increase in alerts that may not be beneficial to the controller [Paglione and Oaks, 2009].

This study evaluates the benefits of a potential enhancement to the ERAM Trajectory Modeler (TM), a BADA-based KVM algorithm that affects Top of Descent (TOD) prediction and descent rate by making use of an environment in which a greater degree of intent information about each flight is available. Even without richer intent information, the KVM is expected to provide significant improvement for the subset of flights that exhibit continuous or near-continuous descent profiles at or near idle thrust. CDA flights engaging in idle descent is the default assumption of the KVM. Trajectories of flights that follow profiles consistent with step descent or powered descent would not be consistently improved by the KVM enhancement and, in fact, may be degraded around the TOD.

An examination of flights chosen for having CDA-like characteristics reveals that the KVM prototype alone does improve average TOD prediction, reducing the magnitude of error by over 50% from about 150 sec. to about 70 sec (Table 1). Vertical error is reduced by almost 4000 ft. (bottom half of Figure 2), a direct result of the reduced error in TOD prediction. Along track error is also reduced, and the benefit over the descent moves toward 1.5 NM at about 10 minutes from TOD (bottom part of Figure 3). When the additional intent information from pseudo GIM-S messages is included in the process, TOD prediction and along track error are reduced even further (100 sec. and 2.0 NM). Visual evidence of these effects is established in the first two flight examples, while the third example demonstrates what can happen to the TOD and descent prediction when the CAS is not modeled properly, the speed profile is either not followed or is incorrect, or when the KVM prototype is applied to a flight not engaging in typical CDA behavior.

In an effort to compare the effects of implementing the KVM prototype as a replacement to the legacy ERAM TM as opposed to implementing the proposed Hybrid model, trajectory accuracy differences between the Baseline and KVM-All scenarios were examined. Results suggest that implementing the KVM prototype for all flights does not have a deleterious effect on trajectory accuracy in the vertical dimension, at least for the single scenario evaluated for this experiment. Since the KVM used the default BADA speeds in the KVM-All scenario, this suggests that the BADA default speeds are closer to the true cruise speeds than the speeds contained in the ERAM Aircraft Characteristics tables, (legacy kinematic model) used in the Baseline scenario. This is not to suggest that the KVM should be applied to all flights regardless of descent profile, however. This situation could potentially be due to the airspace tested (ZSE), the scenario date tested (3/14/2014), or to some other factor totally independent from the type of trajectory modeling. In addition, the non-degradation in the vertical dimension is contingent on how interim altitude clearances are applied after the 25 minute freeze horizon used in this experiment. Interim clearances provided by controllers can cause the observed descent path of a flight to deviate significantly from the path predicted by the KVM (assumption of near-idle descent), which may lead to significant degradation to the accuracy of the KVM-built trajectory. This kind of error cannot be improved through manipulation of the KVM, as it is unrelated to the physical processes that the prototype attempts to model.

Overall, large improvements in the TOD prediction, vertical error, and along track error suggest that the implementation of the KVM would benefit descent prediction in ERAM. Application of the KVM to CDA flights while using the legacy TM for prediction of non-CDA descents is exactly the Hybrid KVM Model proposed in [Torres and Dehn, 2014]. As long as a means for identifying CDA flights in real or near-real time in the NAS exists, either through GIM-S messages (part of TBFM) or some other means, the Hybrid model can be implemented regardless of the actual amount of CDA flights being flown. As CDA flights become more prevalent, the result would be less use of the legacy TM as flights approach their TOD and a greater manifestation of the performance improvements associated with the KVM.

In conclusion, it is recommended to continue development and evaluation of the KVM prototype with additional scenarios from different facilities in order to better generalize the results. And while accuracy of the TP was the focus of this paper, it is important to consider the overall effect of KVM on CP performance, which can be evaluated in future work. In addition, future work may need to consider qualitative issues such as a possible preference for early TOD prediction over late prediction or other aspects that may be more complex than an assessment based solely on accuracy. This initial study indicates that KVM will provide substantial improvement to ERAM's performance, and it is predicted that as the number of CDA flights that perform these efficient and environmentally friendly idle-thrust descents increases, the Hybrid-KVM will allow ERAM to reap further benefits in prediction performance leading to better separation management service by air traffic control for the airline users and ultimately the flying public.

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